



## Assessing the impact of water reuse for agricultural and urban irrigation based on the ecosystem service framework: evidence from a German case study

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### ABSTRACT

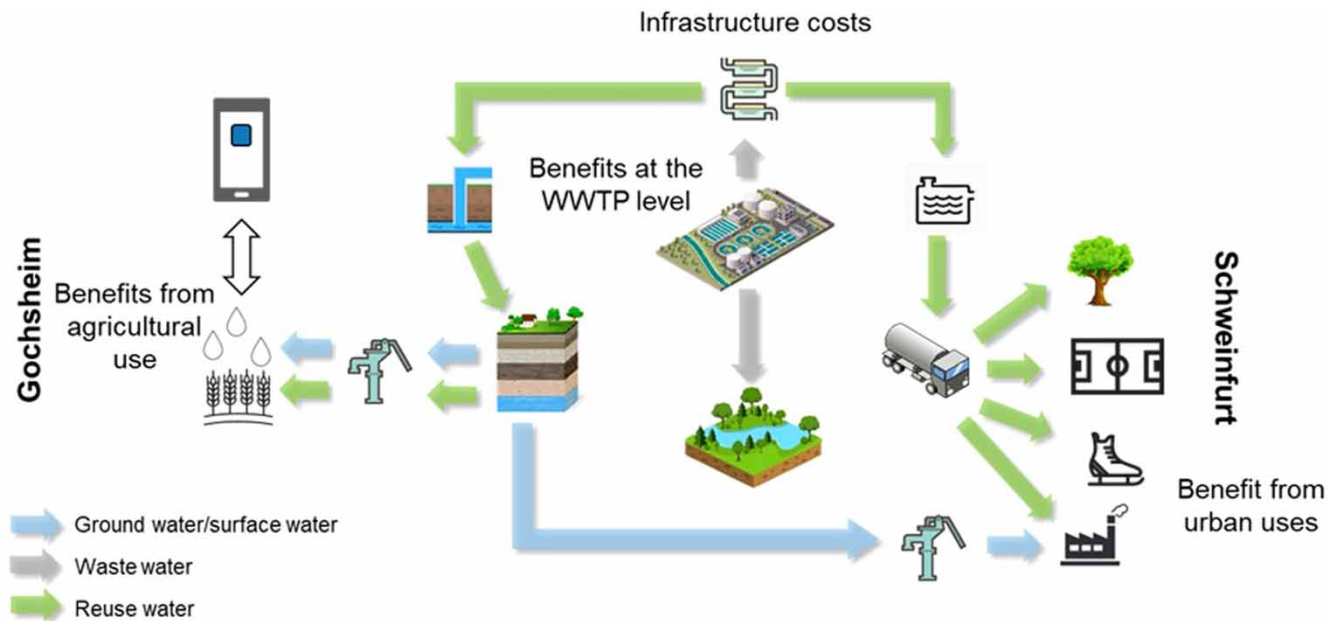
Facing changing conditions like climate change, water-stressed regions are exploring alternative water supply options, including water reclamation for agricultural and urban irrigation purposes. While required technologies are available, highly flexible and demand-driven management strategies for water reuse in urban and agricultural irrigation are still in an early stage of development, especially in Germany. The project 'Nutzwasser' successfully demonstrated a water reuse system using advanced treated municipal wastewater for agricultural and urban irrigation and performed a holistic cost-benefit analysis (CBA) to assess the economic feasibility of the approach. This CBA combines the concepts of life cycle costing and ecosystem services, which were used to develop a use-case-specific indicator-based evaluation matrix with decision-relevant economic indicators and ecological endpoints. The matrix was then applied to a German case study in order to quantify the technology-induced changes in local ecosystem services and their corresponding costs. The application of the assessment approach proved that the ecosystem service concept is suitable for showcasing the benefits of water reuse systems. At the same time, it became evident that there is further improvement needed in order to overcome existing challenges with regard to input data availability.

**Key words:** agricultural irrigation, cost-benefit analysis, ecosystem services, life cycle costing, urban irrigation, water reuse

### HIGHLIGHTS

- New assessment approach for cost-benefit analysis of water reuse systems combining life cycle costing and ecosystem services evaluation.
- Assessment results from a German case study, including different use cases and demand scenarios for urban uses and agricultural irrigation.

## GRAPHICAL ABSTRACT



## INTRODUCTION

In regions experiencing water scarcity with seasonal fluctuations, the discrepancy between the seasonal variation of water demand and the availability of freshwater resources can be significant. Therefore, untapping alternative water resources and water reuse in particular become an indispensable element of future sustainable water supply concepts in many European countries, also including Germany. It is expected that reclaimed water, as an additional water resource in water-scarce or densely populated regions with high irrigation demands, will constitute an essential part of the urban water cycle in the long run (Wintgens *et al.* 2006).

Although the European regulatory framework for water reuse in agricultural irrigation was established with the publication of Regulation 2020/741 on minimum requirements for water reuse (European Commission 2020), the widespread adoption of water reuse technologies remains limited due to insufficient public acceptance and the significant investment costs involved in water reuse processes and infrastructure (Hartley *et al.* 2019; Lee & Jepson 2020).

Water reuse requires substantial capital expenditures, which regularly include the cost for civil work, equipment, studies and projects, supervision, advisory, and land acquisition (Pinheiro *et al.* 2018). High peak demands can be a major driver for the investment costs of water provision. Therefore, small-scale, decentralized technologies to enhance water reuse applicability and reduce the stress on freshwater sources are receiving increasing attention (Reynaert *et al.* 2021). In any case, a clear distinction between centralized and decentralized systems is required for any cost analysis of reuse systems (Salgot & Folch 2018). Although capital costs can constitute a significant portion of the total expenses, annual operational costs, including labour, component maintenance, and energy, should also be considered when making decisions about water reuse projects (Cagno *et al.* 2022). In general, the total costs for water reuse can only be recovered over a realistic timeframe if high delivery volumes can be expected, which is unlikely considering the seasonal reclaimed water demand. Therefore, flexible and demand-driven management and financing strategies are essential for water reuse in urban and agricultural settings. This includes alternative processes that can deliver recycled water cost-effectively and on demand, promoting the rapid adoption of water reuse in regions experiencing seasonal water stress.

Moreover, recent studies on water reuse acceptance indicate that negative public perception remains a barrier to its adoption, despite its significant potential to provide broader societal and ecological benefits. Analysing the benefits of water reuse projects using reliable data and clear evaluation methods, and effectively communicating these insights in stakeholder dialogues, can be crucial in raising public awareness and acceptance of alternative water supply solutions (Hartley *et al.* 2019).

So far, irrigation has played only a marginal role in Germany, comprising about 3.3% of the agricultural area (Statistisches Bundesamt 2024). However, due to increasing drought in recent years, which resulted in increasing pressure on water resources, there is an increasing demand for alternative irrigation water supply (Umweltbundesamt 2023).

The aim of the transdisciplinary research project ‘Nutzwasser: Non-potable water supply and planning options for urban and agricultural irrigation’ funded by the German Federal Ministry of Research, Technology and Space (BMFTR) was the development of new, highly flexible and demand-oriented management strategies for water reuse for urban and agricultural irrigation. To assess the costs and benefits of reusing treated municipal wastewater effluents, a comprehensive evaluation approach was developed and implemented. This approach considers both the economic and environmental impacts of various treatment schemes for water reclamation within the framework of a national case study. In the subsequent sections, the methodological approach and the framework conditions of the case study are described. Furthermore, the applicability of the assessment approach to evaluate the costs and benefits of three reuse water scenarios under different premises is demonstrated in a German case study.

## METHODS

### Cost–benefit analysis

Cost–benefit analysis (CBA) is a monetary evaluation procedure for the comparative evaluation of objects or alternative courses of action. By comparing the result (the benefit) and the effort (the costs) of a measure, it serves as a decision-making aid regarding the implementation and selection between different measures. The decision rule is that a measure or project should generally be implemented if the ratio of benefits to costs is greater than one. In practice, however, a higher ratio is often required (Hein *et al.* 2015).

CBA is frequently used as a holistic assessment approach in decision-making processes for water-related investment projects, as it provides the opportunity to include any type of relevant assessment criteria, mostly from a social, environmental, and economic perspective (Ratnaweera *et al.* 2021). Also, in the context of water reuse projects, CBA has been an incremental part of the decision-making process in various case studies (Molinos-Senante *et al.* 2011; Kihila *et al.* 2014; Garcia & Pargament 2015; Wahid *et al.* 2024). However, the selection of environmental and social indicators in these studies was usually based on expert judgement, stakeholders’ preferences, criteria defined by the regulator, legislative initiatives, or guidelines for the application of CBAs. Any paper identified in a focused literature review on CBAs for water reuse solutions that was performed in the course of this study has established a direct link to the ecosystem service (ESS) concept (Millennium Ecosystem Assessment 2005). To transform the concept of ecosystem services into a practice-oriented approach, Anzaldúa *et al.* (2018) developed the ‘DESSIN ESS Evaluation Framework’ to evaluate changes in ESS associated with technical or management solutions implemented at the water body, sub-catchment, or catchment level. It was developed with a specific focus on freshwater ecosystems and builds upon existing classification systems for ESS, such as the Common International Classification of Ecosystem Services (CICES), the Driver, Pressure, State, Impact, Response (DPSIR) adaptive management scheme, and the Final Ecosystem Goods and Services-Classification System (FEGS-CS) with the aim to promote more informed decision-making and support innovation uptake. The framework combines these different classification schemes in an assessment approach consisting of five parts: study description, problem characterization, response capabilities and potential beneficiaries, impact evaluation, and sustainability assessment.

Within the CBA approach developed as part of the water reclamation project of this study, the ecological benefits were assessed based on alignment with part IV of the ‘DESSIN ESS Evaluation Framework’, starting with a selection of relevant ESS from the CICES classification. This resulted in a use-case-specific but transferable ESS evaluation matrix. The selected ESS were assessed with regard to the ESS provision (called Impact I in the ‘DESSIN ESS Evaluation Framework’) and ESS use and resulting benefits (called Impact II in the ‘DESSIN ESS Evaluation Framework’) (Anzaldúa *et al.* 2018).

The cost assessment in this CBA was carried out using life cycle costing. In principle, all costs from development through utilization to the end of life are considered (Blanchard & Fabrycky 2006). Different scenarios were evaluated dynamically by applying the net present value method over a defined period. To compare different scenarios, the cost items of the additional wastewater treatment steps were calculated in a modular way so that the treatment steps and their size could be adapted easily to the individual demand forecasts for reuse water.

Based on this evaluation approach, a CBA for a German case study was conducted. The economic data required for the assessment were produced as part of the project. The case study owner, the local wastewater utility, provided additional information on social aspects based on stakeholder consultation and expert opinion.

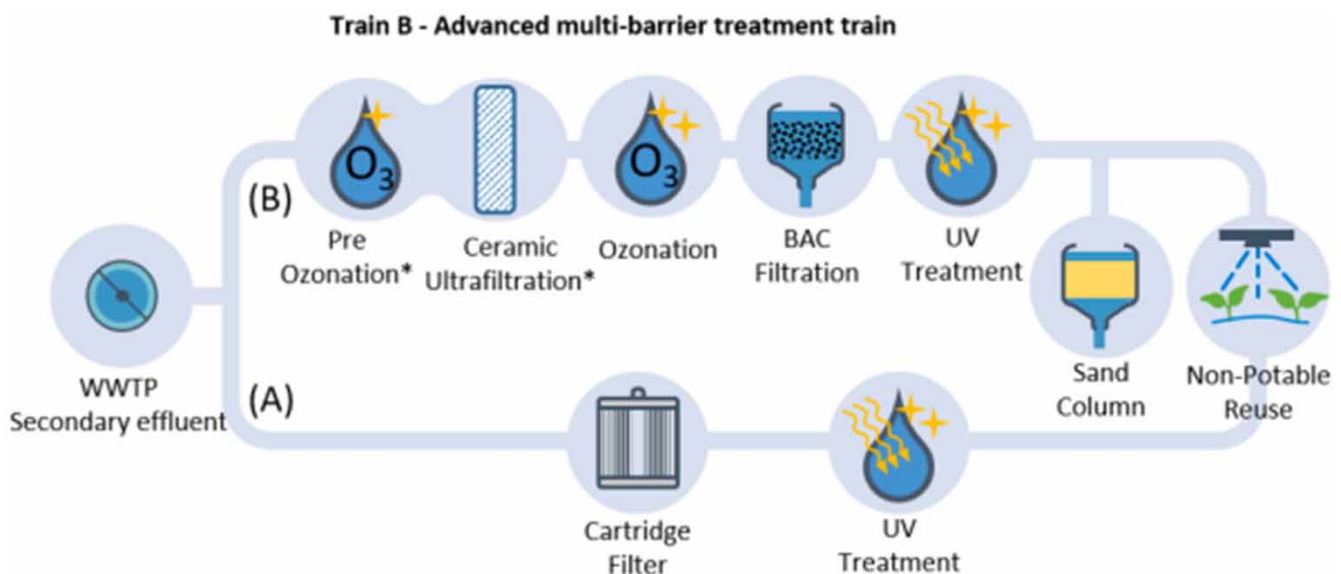
### Case study description

In Southern Germany, the wastewater treatment plant (WWTP) of the city of Schweinfurt ensures wastewater treatment for municipal and industrial customers. The area around Schweinfurt is a region with traditionally pronounced water scarcity, in which water use conflicts are increasingly occurring due to the effects of climate change. It is representative of many regions in Germany, Europe, and other locations that are facing a new water management situation and in which there is an urgent need to explore unconventional solutions.

As part of this study, innovative multi-barrier treatment technologies for the efficient reduction of microbiological and chemical contaminants were demonstrated in a pilot plant (Figure 1). Two different treatment trains were tested and evaluated to meet the microbial and chemical requirements of the new European non-potable water reuse regulation (WRR) 2020/741. Train A was comprised of conventional activated sludge (CAS) treatment followed by a filtration and a UV disinfection step. Train B was comprised of CAS followed by (pre-ozonation), ceramic ultrafiltration (UF), ozonation, and UV disinfection. For further information regarding the performance of these treatment trains, please refer to Ho *et al.* (2024). Based on the results of the study, a risk-based contaminant framework to comply with the EU non-potable reuse regulation was developed and applied (Ahmadi *et al.* 2025).

In addition, a digital approach to predicting reuse water demand for urban and agricultural irrigation was developed. Reliably forecasting this demand enables flexible supply and allows the purification process to be initiated in good time to meet peak demand during dry periods. To do so, an existing irrigation demand app was extended for the automated data assessment, archiving, and determination of the irrigation requirement, considering local and regional weather data, as well as field-related data in real time. With the help of the irrigation app, the urban and agricultural case study areas can now be irrigated based on the specific agronomic rate as required and in a water-saving manner.

The CBA considers two different application areas for the treated wastewater: (i) urban irrigation and industrial applications in the city of Schweinfurt and (ii) agricultural irrigation in the city of Gochsheim. To determine the best-suited design of the treatment plant and supply infrastructure, as well as the benefits of water reuse for both application areas, the reuse water demand was determined in a first step.



**Figure 1** | Conceptual layout of the two parallel multi-barrier treatment trains (A and B) at the Schweinfurt water reclamation facility. \*Train B was operated with and without pre-ozonation and UF (Ho *et al.* 2024).

In Schweinfurt, various possible uses of reuse water in the urban area could be realized. These uses include the irrigation of sports facilities like a stadium or sports field, public green spaces, and the area of a newly developed city park. However, an application in the ice stadium and the utilization of reuse water in industry (e.g. a laundry) could also be possible applications for the reuse water. The water reclamation demand forecast for Schweinfurt, which was determined in consultation with the local stakeholders, who are responsible for the irrigation of the areas, differentiates between irrigation in the summer months (April–September) and the winter months (October–March). The weekly water demand forecast in irrigation processes in m<sup>3</sup>/week for Schweinfurt can be found in Table 1 for the summer months and in Table 2 for the winter months. Taking all possible uses into account, the current potential demand for reuse water is ca. 200,000 m<sup>3</sup>/a. This value is the minimum water demand considered in the CBA and resembles the commitments of the relevant stakeholders. It is expected to increase over time.

In collaboration with stakeholders, it was estimated that up to 40% of the reclaimed water generated during the irrigation season (April–September) would be used in the future. This reuse is expected to help meet the long-term water demand for both urban and agricultural irrigation, with a maximum projected water demand of 1,790,000 m<sup>3</sup>/year. The minimum and maximum water demand values were considered in the CBA.

According to the investigations of a preliminary project, there are approximately 130 ha of agricultural land in the Gochsheim region that can be irrigated for vegetable cultivation, of which an average of 40–60 ha usually needs to be irrigated (Schwaller *et al.* 2020). Direct water supply from local groundwater resources close to the sites is the current source for irrigation. Groundwater abstraction is currently approved for 100,000 m<sup>3</sup>/year in total, which can be drawn from 36 installed wells (Schwaller *et al.* 2020). This corresponds to the quantities that were actually required in dry years such as 2015 or 2018.

Table 3 summarizes the reuse water demand forecasts in Schweinfurt and Gochsheim.

## RESULTS AND DISCUSSION

### ESS evaluation matrix for water reuse applications

One of the key objectives of this study was to develop a CBA approach based on the ESS concept to evaluate different water recycling solutions. Table 4 presents identified potentially relevant ESS for water reuse for urban uses and agricultural

**Table 1** | Water demand forecast for urban irrigation in Schweinfurt in m<sup>3</sup>/week (April–September)

	Apr	May	Jun	Jul	Aug	Sep
Park	300	300	600	600	600	300
Stadium	800	800	1,410	1,410	1,410	800
Public green areas	180	180	300	300	300	180
Sports field	90	90	180	180	180	180
Ice stadium						123
Laundry	1,350	1,350	1,350	1,350	1,350	1,350
<b>Sum</b>	<b>2,720</b>	<b>2,720</b>	<b>3,840</b>	<b>3,840</b>	<b>3,840</b>	<b>2,843</b>

**Table 2** | Water demand forecast for urban irrigation in Schweinfurt in m<sup>3</sup>/week (October–March)

	Oct	Nov	Dec	Jan	Feb	Mar
Park						
Stadium	200					
Public green areas						
Sports field	90					
Ice stadium	33	33	33	33	33	33
Laundry	1,350	1,350	1,350	1,350	1,350	1,350
<b>Sum</b>	<b>1,673</b>	<b>1,383</b>	<b>1,383</b>	<b>1,383</b>	<b>1,383</b>	<b>1,383</b>

**Table 3** | Reuse water demand forecasts for Schweinfurt and Gochsheim

	Reuse water demand forecast
Schweinfurt (minimum)	200,000 m <sup>3</sup> /a
Schweinfurt (maximum)	1,790,000 m <sup>3</sup> /a
Gochsheim	100,000 m <sup>3</sup> /a

irrigation based on the CICES list. The evaluation matrix helps users to identify the socioeconomic advantages and disadvantages of different water reuse system configurations. For each ESS, specific assessment criteria were suggested. The potentially relevant assessment criteria should be reviewed based on the particular decision case, and only case-relevant ESS should be selected for the following environmental and economic assessment. Involving experts from various disciplines in the selection process can help ensure that conflicting stakeholder perspectives on water reuse technology implementation are considered during the assessment.

In general, the evaluation methods used to generate the necessary benefit estimates for CBA may vary depending on the assessment criteria. For instance, the provisioning ESS of biomass and water can be evaluated by estimating potential crop losses or assessing farmers' willingness to pay. In contrast, the assessment of regulating and maintenance ESS is most effectively conducted using avoided cost approaches, such as reduced reliance on road tankers for transport and cost savings from damage prevention, such as flood protection. Cultural ESS can be assessed by the travel cost method, which analyses the cost for people to visit the site, by researching and evaluating income from ecotourism, and by surveying the appreciation of the local population. The choice of method depends on the availability of relevant data and the feasibility of collecting relevant data as part of the assessment. In case of insufficient data availability, benefit transfer could also be used as a methodological approach for data acquisition (Gerner *et al.* 2018).

## Case study results

### Cost assessment

On the cost side, various technical options and flow rates for a potential quaternary wastewater treatment (including ozonation (O) and biological activated carbon (BAC)), along with additional advanced treatments (such as UF and UV treatment) at the WWTP in Schweinfurt, were evaluated. Additionally, a quantity- and location-validated infrastructure for Gochsheim and Schweinfurt, as well as the irrigation demand app planned for Gochsheim, were considered. The cost analysis only included the public supply infrastructure, but not the supply infrastructure on the water user's property.

To compare different scenarios and develop a management strategy, different cost items of the treatment process were divided into modules that reflect the different water treatment steps, and the system size required to provide either the minimum or the maximum water demand for urban irrigation. Table 5 provides an overview of the cost modules and their characteristics.

The technical characteristics of the planned treatment processes are similar to the treatment train B tested in the pilot plant within the water reclamation project (Figure 1). The future water reclamation facility will be designed for a planned capacity of 1,790,000 m<sup>3</sup>/a, which allows for a full coverage of the forecasted maximum urban irrigation and industrial reuse water demands in the city of Schweinfurt, as well as the forecasted reuse water demands in Gochsheim. Cost data for water treatment, required infrastructure, and the operational costs for hosting the irrigation demand app were calculated in the project. Table 6 shows the main life cycle costing assumptions.

### Benefit assessment

From the list of the potentially relevant ESS for water reuse for urban uses and agricultural irrigation based on the CICES list (Table 4), only a limited number of ESS were considered as relevant for the specific case study under investigation.

Based on the expert estimation of the local farmers, there would be no crop losses if reused water were unavailable during dry periods, as a crop rotation would likely occur, resulting in minimal impact on revenue from crop yields. The quantification of the ecological impact of water reuse on the provision of regulating and maintaining ESS was not possible in the project due to limited data availability. However, in general, it can be assumed that biological, chemical, and ecological risks are negligible, as a thorough risk assessment is necessary to obtain approval for the implementation of the water reuse solution. Odour

**Table 4** | Potentially relevant ESS for water reuse for urban uses and agricultural irrigation based on the CICES list

Section	Division	Group	Class	Code	Evaluation criteria	
Provisioning	Biomass	Cultivated terrestrial plants for nutrition, materials, or energy	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes	1.1.1.1	Reduction of crop losses by increasing the security of water supply	
			Cultivated plants (including fungi, algae) grown as a source of energy	1.1.1.3	Reduction of crop losses by increasing the security of water supply	
	Water	Groundwater used for nutrition, materials, or energy	Groundwater (and subsurface) for drinking	4.2.2.1	Avoided groundwater utilization/increase in the groundwater table/additional available water volume	
			Groundwater (and subsurface) is used as a material (non-drinking purposes)	4.2.2.2	Avoided groundwater utilization/increase in the groundwater table/additional available water volume	
Regulation and maintenance	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes Mediation of nuisances of anthropogenic origin	Filtration/sequestration/storage/accumulation by microorganisms, algae, plants, and animals	2.1.1.2	Biological/chemical/ecological risks	
			Smell reduction	2.1.2.1	Odour pollution	
			Noise attenuation	2.1.2.2	Noise pollution	
	Regulation of physical, chemical, and biological conditions	Regulation of baseline flows and extreme events Regulation of soil quality Water conditions Atmospheric composition and conditions	Hydrological cycle and water flow regulation (including flood control and coastal protection) Weathering processes and their effect on soil quality Decomposition and fixing processes and their effect on soil quality Regulation of the chemical condition of freshwaters by living processes Regulation of temperature and humidity, including ventilation and transpiration	Visual screening	2.1.2.3	Aesthetics/integration into nature/space requirements
				Change in the water balance (evaporation quantities, infiltration quantity, surface runoff)	2.2.1.3	Change in the water balance (evaporation quantities, infiltration quantity, surface runoff)
				Soil quality/soil fertility	2.2.4.1	Soil quality/soil fertility
				Soil quality/soil fertility	2.2.4.2	Soil quality/soil fertility
Groundwater quality	Groundwater quality (Economic value of good groundwater quality)	Groundwater quality	2.2.5.1	Groundwater quality (Economic value of good groundwater quality)		
			2.2.6.2	Emission of climate-relevant gases/local climate regulation/heat exchange		
Cultural	Direct, <i>in situ</i> , and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with the natural environment	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	3.1.1.1	Income from ecotourism	
			Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment	3.1.1.2	Beauty of the landscape	

(Continued.)

Table 4 | Continued

Section	Division	Group	Class	Code	Evaluation criteria
			through passive or observational interactions		
		Intellectual and representative interactions with the natural environment	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	3.1.2.1	Strengthening environmental awareness
			Characteristics of living systems that enable education and training	3.1.2.2	Capacity of the area to provide educational programmes

Table 5 | Cost modules for scenario creation

	Cost module	Characteristics
Quaternary + further treatment	Quaternary treatment	Ozonation – BAC
	Further treatment train options	Option 1: UF – UV Option 2: UV
	Size of further treatment train (m <sup>3</sup> /a)	1,790,000 m <sup>3</sup> /a 200,000 m <sup>3</sup> /a
	Flow rate of further treatment train (m <sup>3</sup> /a)	1,790,000 m <sup>3</sup> /a 200,000 m <sup>3</sup> /a
	Inclusion of quaternary treatment costs	Yes No
	Possible funding of quaternary treatment considered	Yes No
	Amount of funding	Can be entered as a percentage (50% is used)
Infrastructure	Infrastructure Schweinfurt	Piping, steel tank (1.000 m <sup>3</sup> ), pumping station
	Infrastructure Schweinfurt Laundry	Yes, 1 km of additional piping No, no additional piping
	Infrastructure Gochsheim	Piping, pumping station, trenches
Irrigation demand app Gochsheim	Implementation, operation, and maintenance costs	Yes No
		Yes No
	Development costs	Yes No

or noise pollution, as well as constraints related to aesthetics or space, are not relevant in this case since the treatment facility will be located near the local WWTP, and the pipeline network will be underground. These estimates were made on expert judgement by local stakeholders. However, further investigation of the ESS on regulation and maintenance is recommended to be assessed in future studies in order to enable a comprehensive and fully reliable assessment based on measured data.

Therefore, after the selection of case-relevant ESS, only four ESS were remaining for assessment, and different evaluation approaches were defined for their assessment.

The provisioning ESS has been assessed in the course of a stakeholder consultation with the local farmers. The benefits from avoided groundwater abstraction were assessed based on a willingness-to-pay study for irrigation water with local farmers. Based on the information gathered in stakeholder workshops in Gochsheim, the willingness to pay by local farmers engaged in high-value crop farming was up to 0.50 €/m<sup>3</sup> of irrigation water. The study results were cross-checked based on a literature study, revealing that this value is much higher than all results derived from studies in other regions of Germany or Europe (Menegaki *et al.* 2007; Souza *et al.* 2017), already considering that these literature values need to be corrected based on a suitable benefit transfer approach (Anzaldúa *et al.* 2018). Therefore, the willingness to pay stated by the local farmers was replaced by a more conservative cost estimate based on the costs for irrigation of 0.30 €/m<sup>3</sup> reported in a recent German case study (Ebert *et al.* 2019). The willingness-to-pay value finally included in the benefit calculation can therefore be seen as a lower limit for the willingness to pay. One suspected reason is that specialty crop farmers, such as those in

**Table 6** | Operational cost rates

	Amount	Unit
Energy	0.30	€/kWh
Precipitants	165	€/t
Oxygen	300	€/t
NaOCl	2.55	€/l
Citric acid	0.95	€/l
Granulated active carbon	2.200	€/t
Cooling water for ozonation	0.02	€/m <sup>3</sup>
Sludge disposal	120	€/t
Personnel costs	50	€/h
Personnel hours	5	h/d
Working days per year	250	d/a
Lifespan of buildings	30	a
Lifespan of machinery	15	a
Lifespan of electronic instrumentation and control	15	a

Gochsheim, might have a very high willingness to pay for irrigation water due to the strong reliance on regular irrigation for such plants as well as a high awareness of water availability in their region.

An agricultural irrigation water demand of 120,000 m<sup>3</sup>/a was determined in the preliminary study (Schwaller *et al.* 2020). As this forecast is based on dry years, it was decided to use a lower value of 100,000 m<sup>3</sup>/a for the assessment in order to avoid overestimation. Based on this, a willingness to pay of the farmers in Gochsheim of 30,000 €/a was determined.

In terms of urban irrigation, the cost savings for recreational activities (such as ice stadiums) and industries (like laundries) were evaluated as potential indirect benefits resulting from reduced freshwater consumption. This evaluation was based on the difference between the price of reclaimed water, which covers costs, and the price of drinking water, relative to the projected reuse water consumption by users. The current local drinking water price (2024) is 2.30 €/m<sup>3</sup> for a minimum volume of 15,000 m<sup>3</sup>/a. As the cost-covering price for reclaimed water depends on the technical design of the facility, the difference between the two prices varies as well.

The costs of the quaternary treatment can be charged as part of the regular wastewater treatment via wastewater bills. Therefore, this benefit item is recognized in the amount of the costs incurred.

The cultural ESS was summarized and evaluated by assessing the appreciation of Schweinfurt's residents for public green spaces. The residents' appreciation of public green spaces was determined by data from an online questionnaire created in the project. This survey determined a willingness to pay for the maintenance of public green spaces of 53.19 € per person and year, which was extrapolated to all Schweinfurt residents subject to social security contributions (Statistics from the Federal Employment Agency 2022). This resulted in a value of 1,122,828.33 €/a for the public appreciation of green spaces in Schweinfurt. A literature review on willingness to pay for the maintenance of public green spaces by citizens revealed a range between 21 €/a in Crete (Souza *et al.* 2017), 61.56 €/a in Italy (Alcon *et al.* 2010), and 85.68–108.12 €/a in Joensuu, Finland (Tyrväinen 2001). Based on the fact that the willingness to pay of citizens in Schweinfurt is on a lower payment level compared with studies conducted in other central European countries leads to the estimate that the determined willingness to pay is reasonable and appropriate.

However, when dealing with willingness-to-pay studies, it is important to note that the value calculated in this manner does not serve as a comparative figure for any payment flows. Instead, it acts as a proxy for the social value of non-priced environmental goods, aiding in the welfare-economic estimation of the hypothetical willingness to pay.

### CBA of different scenarios

Due to the modular design of the cost and benefit assessment, it was possible to assess many different scenarios by CBA. In the following, only three scenarios will be presented (Table 7):

**Table 7** | Scenarios for assessment

	Scenario 1	Scenario 2	Scenario 3
Quaternary treatment	Ozonation – BAC	Ozonation – BAC	Ozonation – BAC
Further treatment train option	Option 2: UV	Option 2: UV	Option 2: UV
Size of further treatment train	200,000 m <sup>3</sup> /a	1,790,000 m <sup>3</sup> /a	1,790,000 m <sup>3</sup> /a
Flow rate of further treatment train	200,000 m <sup>3</sup> /a	1,790,000 m <sup>3</sup> /a	1,790,000 m <sup>3</sup> /a
Inclusion of quaternary treatment costs	Yes	Yes	Yes
Possible funding of quaternary treatment considered	Yes	Yes	Yes
Amount of funding	50%	50%	50%
Infrastructure Schweinfurt	Piping, steel tank (1.000 m <sup>3</sup> ), pumping station	Piping, steel tank (1.000 m <sup>3</sup> ), pumping station	Piping, steel tank (1.000 m <sup>3</sup> ), pumping station
Infrastructure Gochsheim	Piping, pumping station, trenches	Piping, pumping station, trenches	–
Irrigation demand app Gochsheim: Implementation, operation, and maintenance costs	No	No	No
Irrigation demand app Gochsheim: development costs	No	No	No
Schweinfurt laundry: Infrastructure costs	No	Yes	Yes
Schweinfurt laundry: Benefit through cost savings	No	Yes	Yes

- Scenario 1: Lowest costs
- Scenario 2: Highest benefit from water reuse
- Scenario 3: Exemplary selected scenario for Schweinfurt

The scenarios were chosen based on the principles of lowest cost (scenario 1), greatest benefit from water reuse (scenario 2), and implementation in Schweinfurt alone (scenario 3). The modules in scenario 3 were selected based on the strategic decision to achieve economies of scale. Consequently, the modules with the highest flow rate and the lowest cost were selected, bearing in mind the potential for future use in areas such as the laundry.

Prerequisites for all three scenarios are that the quaternary treatment is billed via the wastewater charge and subsidized with 50% of the investment costs. In addition, revenues from the sale of reclaimed water are only expected if the price of reclaimed water is below the price of drinking water of 2.30 €/m<sup>3</sup> for a minimum volume of 15,000 m<sup>3</sup>/a in Schweinfurt.

For all scenarios, the cost-covering reclaimed water price was calculated for the minimum and maximum water demand. In addition, the break-even point (BEP) was calculated for the amount of water produced at which the reclaimed water price falls below the drinking water price, and thus, revenues can be generated in the industrial/commercial and leisure sectors. The cost-covering price is determined by the annual costs, which are based on the net present value of all cost factors, including the entire distribution networks in Schweinfurt and Gochsheim, the quaternary treatment, additional treatment for water reuse, and, if selected, the irrigation demand app in Gochsheim, relative to the sales volume.

The results of the CBA of the different scenarios are shown in Table 8. All scenarios have a positive cost-benefit ratio, meaning that they have a positive economic-ecological impact. As not all ESS in Schweinfurt and Gochsheim could be assessed in monetary terms, the calculated benefit value represents a minimum. The cost-covering prices for reclaimed water, assuming the minimum water demand, is higher than the current price of drinking water in all scenarios. A higher volume of reclaimed water production and application would not only lower the specific costs for reclaimed water production but also increase the benefits associated with its use. This observation is common for innovative water reuse technologies, as they typically incorporate various water treatment methods (multi-barrier treatment strategies) and are currently deployed on a much smaller scale than centralized water treatment facilities. In order to achieve a lower price for reuse water than for

**Table 8** | Scenario comparison of CBA results

	Scenario 1	Scenario 2	Scenario 3
Present value of costs	88,528,430 €	96,624,430 €	90,136,222 €
Present value of benefit	104,159,174 €	111,057,336 €	110,227,069 €
Cost–benefit ratio	1.18	1.15	1.22
Reuse water price (minimum water demand)	2.94 €/m <sup>3</sup>	4.40 €/m <sup>3</sup>	3.23 €/m <sup>3</sup>
Reuse water price (maximum water demand)	– <sup>a</sup>	0.52 €/m <sup>3</sup>	0.36 €/m <sup>3</sup>
BEP volume (reuse water price vs. drinking water price)	– <sup>a</sup>	385,000 m <sup>3</sup> /a	285,000 m <sup>3</sup> /a

<sup>a</sup>Scenario 1, as the lowest cost scenario, only includes a treatment with a dimension of 200,000 m<sup>3</sup>/a. Therefore, the maximum water demand cannot be covered and the critical volume to generate sales revenues from reuse cannot be reached.

regional drinking water, a minimum of 385,000 m<sup>3</sup>/year of reuse water needs to be sold in scenario 2, and 285,000 m<sup>3</sup>/year in scenario 3. In scenario 1, it is not feasible to achieve a price below the drinking water price as the capacity of the treatment is limited to 200,000 m<sup>3</sup>/a.

The decision between these exemplary scenarios is strategic. A dimensioning of 200,000 m<sup>3</sup>/a, like in scenario 1, corresponds to the current water demand forecast, but here the cost-covering price is higher than the drinking water price (as of 2024). With a larger dimensioning and an expansion of the sales volume, cost-covering prices of approximately 0.38–0.52 €/m<sup>3</sup> can be achieved due to the economies of scale.

A sensitivity analysis was carried out changing the amount of public funding (Table 9), the inclusion of the quaternary treatment costs (Table 10), the discount rate (Table 11), and the price increase rate (Table 12). The analyses support the robustness of the results, as nearly all benefit-cost ratios remain above 1, and therefore, the benefit is higher than the costs. The only exception to a cost–benefit ratio below 1 is a price increase rate of 5% in scenario 2 (Table 12).

**Table 9** | Sensitivity analysis of public funding

	Public funding	
	0%	50%
Cost–benefit ratio: Scenario 1	1.16	1.18
Cost–benefit ratio: Scenario 2	1.14	1.15
Cost–benefit ratio: Scenario 3	1.20	1.22

**Table 10** | Sensitivity analysis of the inclusion of quaternary treatment costs

	Inclusion of quaternary treatment costs	
	Not included	Included
Cost–benefit ratio: Scenario 1	2.0	1.18
Cost–benefit ratio: Scenario 2	1.6	1.15
Cost–benefit ratio: Scenario 3	2.1	1.22

**Table 11** | Sensitivity analysis of discount rate

	Discount rate		
	1%	3%	5%
Cost–benefit ratio: Scenario 1	1.15	1.18	1.19
Cost–benefit ratio: Scenario 2	1.12	1.15	1.17
Cost–benefit ratio: Scenario 3	1.20	1.22	1.24

**Table 12** | Sensitivity analysis of price increase rate

	Price increase rate		
	1%	3%	5%
Cost–benefit ratio: Scenario 1	1.42	1.18	1.02
Cost–benefit ratio: Scenario 2	1.37	1.15	0.98
Cost–benefit ratio: Scenario 3	1.45	1.22	1.05

The sensitivity analyses show that price increase rates and the inclusion of quaternary treatment costs strongly influence the cost–benefit ratios, whereas the discount rate and public funding only have a limited influence. Quaternary treatment costs account for around 80% of the total costs. These costs cover initial investments, reinvestments, and operating costs. Public funding of the quaternary treatment only affects its initial investments (around 13% of quaternary treatment costs), which explains its comparatively low impact on the cost–benefit ratio.

## LIMITATIONS

Due to its theoretical funding based on the ESS concept, the presented CBA approach itself can be easily adapted to different environmental and socioeconomic settings. A mandatory requirement for its application is the existence of basic technological concepts for water reuse, which have to be developed and made comparable in advance.

The limitations of the CBA approach described are principally based on data requirements and data availability for the assessment of ESS provision and ESS impact for specific case study contexts. For the case study presented in this paper, limitations with regard to the availability of data were partially overcome by expert judgements from local experts, as well as benefit values derived from a literature review and transferred to the context of the case study described. However, it is clear that both types of assessment approaches can be biased by personal expectations and underlying assumptions about contextual factors as well. Overall, this can lead to an over- or underestimation of the environmental impacts and monetary benefits.

In order to make the assessment approach more suitable for practical decision-making, future research should focus on defining standardized sets of metrics with corresponding assessment approaches that allow for a more detailed and reliable assessment of preselected water reuse options based on limited data. Especially with regard to regulating ESS, such as soil quality, local climate, or health-relevant aspects, further research is needed in order to provide low-cost methods to model the changes in ESS provision over time and easy-to-use evaluation approaches to transfer these parameter values into monetary values.

As the costs and benefits calculated in this paper are highly dependent on the case study context, the transferability of the values to other case studies is not possible without a correction of the monetary values based on economic concepts, such as the benefit transfer method (Johnston *et al.* 2015).

## CONCLUSIONS

Due to high investment costs and the lack of adequate corresponding financing schemes, the costs of the required water treatment infrastructure are a major obstacle for the implementation of water reuse solutions in Germany and Europe as a whole. Although synergy effects can be used with the new regulation from the revised European Urban Wastewater Treatment Directive (UWWTD) with regards to the requirement for further treatment in large-scale WWTPs, a financing gap posing challenges for WWTP and water reuse facility operators can still be observed leading to unfavourable decisions on the implementation of water reuse solutions for agricultural and urban irrigation. However, considering the costs of implementation and operation, only decision-making is too short-sighted, as ESS must be considered for ensuring long-term resilience of our water systems, as requested by the WRR.

The application of the developed CBA approach in a German case study proved that the methodology provides a good basis for the decision-making process concerning water reuse infrastructure and business models.

The assessment results for three different scenarios investigated for the German case study confirm the findings of previous studies that water reuse is associated with high investment costs for infrastructure. Comparing the costs of the minimum cost scenario and the maximum benefit scenario, the benefits increase at almost the same rate as the costs for the capacity increase

of the reuse facility. As the distribution infrastructure is a major cost driver for reuse water costs, disproportionate increases in benefits can only be achieved if many different reuse water applications can be realised in a close regional context, just as illustrated in scenario 3. However, it must be stated that in the case that the quaternary treatment costs are included for all three water reuse scenarios in Schweinfurt, the benefit-cost ratio is only positive if the quaternary treatment is billed via the wastewater charge in order to ensure that revenues from the sale of reclaimed water can be realized.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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